Performance Tests and Efficiency Analysis of Solar Invictus 53S – A Parabolic Dish Solar Collector for Direct Steam Generation

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Abstract. This paper presents the results of performance tests conducted on Solar Invictus 53S 'system'; an economically effective solar steam generation solution designed and developed by ZED Solar Ltd. The system consists of a dual axis tracking parabolic solar dish and bespoke cavity type receiver, which works as a Once Through Solar Steam Generator 'OTSSG' mounted at the focal point of the dish. The overall performance and efficiency of the system depends primarily on the optical efficiency of the solar dish and thermal efficiency of the OTSSG. Optical testing performed include 'on sun' tests using CCD camera images and 'burn plate' testing to evaluate the sunspot for size and quality. The intercept factor was calculated using a colour look-back method to determine the percentage of solar rays focused into the receiver. Solar dish tracking stability tests were carried out at different times of day to account for varying dish elevation angles and positions, movement of the sunspot centroid was recorded and logged using a CCD camera. Finally the overall performance and net solar to steam efficiency of the system was calculated by experimentally measuring the output steam parameters at varying Direct Normal Insolation (DNI) levels at ZED Solar's test facility in Lahore, Pakistan. Thermal losses from OTSSG were calculated using the known optical efficiency and measured changes in output steam enthalpy.

INTRODUCTION

Concentrated Solar Power (CSP) technologies are perfectly suited for generating steam for applications where process heat is required, other renewable energy systems cannot compete with CSP systems in these domains.

The overall efficiency of a CSP system depends on the combined product of the optical efficiency of the concentrator and thermal efficiency of the receiver. The optical efficiency is measured as the percentage of the DNI reflected and focused into the receiver whereas the thermal efficiency is the percentage of that radiation transferred as heat energy to the heat transfer fluid [1]. Within CSP technologies, parabolic dish concentrators are the most efficient of all solar collector types due to a combination of dual axis tracking and high concentration ratios [2]. The optical efficiencies noted for different dish concentrators range from 78% to 89% [3]. A more recent study reported that 95% of the insolation reflected from a 500 m^2 dish (mirror reflectivity of 93.5%) was focused into a cavity type receiver with an aperture of 500 mm diameter [4]. Improved optics with high concentration ratios directly affects the aperture size of cavity type receiver. A reduction in aperture size from 680 mm to 540 mm would result in 21% lower thermal loses [5]. Direct steam generation achieving 90% thermal efficiency at 535 °C with a parabolic dish and cavity type receiver has been reported based on experimental results using a 500 m^2 dish [6].

Based on the fact that the parabolic dish concentrator and cavity type receiver can achieve very high levels of efficiency, ZED Solar has developed the 'Solar Invictus' to make solar steam cost competitive with traditional energy sources for sectors that need process heat. Solar Invictus is based on parabolic dish and cavity type receiver

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working as a Once Through Solar Steam Generator (OTSSG). The dish concentrator has been designed and built to achieve high concentration ratios based on precision optics enabling a reduced receiver aperture to minimize thermal loses. In addition, the modular and decentralized nature of the system ensures a robust and flexible system that can be installed in variable size arrays with a total capacity starting at just 40 kWth and going up to gigawatt scale. A fully automated cleaning system is integrated into each concentrator which ensures that the mirror surfaces are kept clean while also minimizing costs and water utilization. Each concentrator is mounted on an individual concrete pad making the Solar Invictus the only CSP system which can be relocated without needing to be disassembled.

The first pilot installation of solar dishes was completed in 2014 at the Mohammad bin Rashid Al Maktoum Solar Park, Dubai. This installation verified that the collector can be installed and commissioned quickly and economically and is also able to handle the harsh desert conditions without degradation in optical efficiency or any other problems.

To verify the performance of Solar Invictus dish and OTSSG, several experimental performance tests were carried out using a full suite of sensors and measuring equipment. The optical and thermal efficiencies of the system were determined through the tests and are presented in this paper.

TECHNOLOGY DESCRIPTION

Concentrator Design

The Solar Invictus concentrator is based on a monopole design that enables solar dish installation on inexpensive concrete pad type foundations and requires minimal ground leveling, the monopole design also make the structure and actuation less complex and costly. The innovative and patented parabolic dish design replaces massive space frame structures supporting more traditional solar dishes with light yet highly stiff composite reflective panels that are fastened together and at a central hub in front of the dish. The entire dish structure works in unison to achieve high levels of stiffness against gravitational as well as wind loading with the advantage of lower material cost per kWth, low cost of manufacturing and a modular structure for ease of assembly, shipment and installation. The solar dish with a diameter of approximately nine meters and effective projected area of 51.6 m^2 was designed to operate in high wind speeds of up to 16.66 m/s with negligible effect on performance and survive at 90 degree elevation in winds of 44.44 m/s. The solar dish has a geometric concentration ratio of approximately 2700x and has a sunspot size of approximately 160 mm at its focal point. The composite reflective panels are super stiff and manufactured in a specialized industrial process, which results in fast and easy alignment of the sun dish using an in-house developed aim point strategy. The aim point strategy yields not only a tight sunspot at the focal plane but equally as importantly it achieves intended flux distribution within the sunspot. High performance, low backlash and high-resolution actuators drive the dish in azimuth and elevation axes and are controlled by optimised algorithms to track the sun with great accuracy, thereby completely eliminating cosines losses [7].

Receiver Design

Solar Invictus has a cavity type receiver mounted at the focal point of the solar dish. The receiver works as an OTSSG and is almost completely insulated apart from a small aperture of 190 mm diameter. A coiled standard seamless steel tube heat exchanger inside the cavity absorbs the solar heat and has expansion loops at the inlet and outlet connections to allow for thermal expansion at high temperatures and pressure ratings. Concentrated sunlight enters the OTSSG through the aperture, heats the coil directly and converts the water flowing within the tube to steam in a once through operation. Natural and forced convection losses are at very low levels due to the small aperture area of the OTSSG, which is also the only opening in the receiver. The small aperture helps in achieving large air stagnation zones within the cavity of the OTSSG [8], which in turn reduces the convective heat losses. Conduction induced heat losses are almost negligible for the OTSSG due to extensive insulation and stagnant air zone between the receiver core and the casing. The design has an inherently high effective absorptance, minimizing radiation induced thermal losses [9].

PERFORMANCE TESTING

Optical Efficiency Testing

Ray-tracing software was used to model and analyze the optics of the Solar Invictus dish. The designed allowable surface slope error of the parabolic reflective panels was set to ensure approximately 99.5% of the concentrated sunlight was focused into a 160 mm diameter spot at the focal plane and 99.9% into the 190 mm receiver aperture also at the focal plane. This selection was based on the cost benefit analysis of manufacturing of composite reflective panels.

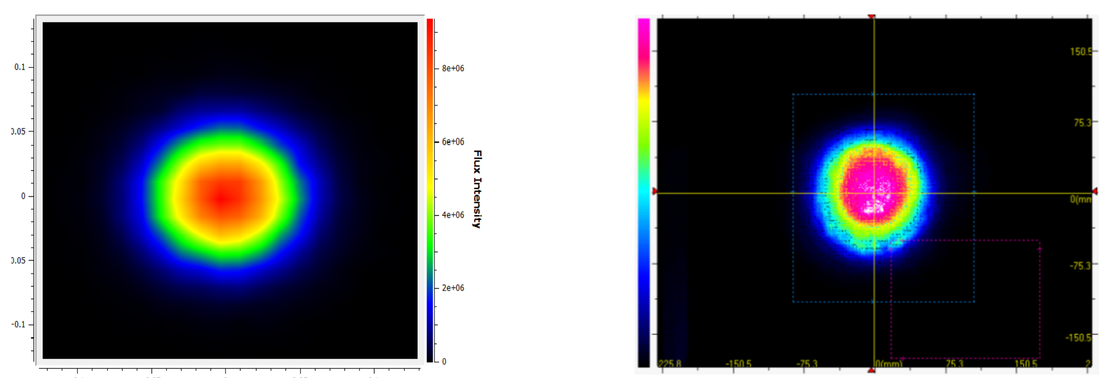
Determining Sunspot Size

The two overriding parameters of the sunspot are the size and quality; a small spot at the focal point allows the receiver to have a small aperture thereby minimizing thermal losses and a high quality spot exhibits intended energy distribution enabling higher heat absorption efficiency. These parameters were tested on multiple Solar Invictus dishes at ZED Solar's facility as well as in all ten dishes installed in the solar park in Dubai. An actuated sunspot-testing rig was mounted on the dish as shown in Fig. 1, the rig can either hold a sand blasted ceramic glass plate for CCD camera images or a steel plate for burn impressions. Using the actuation system the rig can be moved between the focal plane and the receiver plane to take the image or burn impression at the required plane or at any point between the two planes along dish axis. The exposure time was standardised between 5 and 15 seconds dependent upon actual DNI, any prolonged exposure beyond this time frame would result in either melted/shattered ceramic glass or a melted steel plate.

(a) (b)

FIGURE 1. (a) Sunspot testing rig with burn plate, (b) Burn plate test

The sunspot size measured through this test for all dishes included in these tests was found in the range of 150 mm to 160 mm verifying the ray tracing simulation results as well as the manufacturing tolerances and aim point alignment methodology. A comparison of the two is shown in following, Fig. 2.



(a) (b)

FIGURE 2. (a) Ray tracing simulation – spot size (m) at focal plane, (b) CCD camera image of spot size (mm) at focal plane

Intercept Factor Testing

The test described in section 3.1.1 verified the concentrated spot attributes at the focal plane of the dish, however further testing was required to estimate the actual percentage of total reflected sunrays from the mirrors which was being focused into the aperture of the OTSSG. Colour look-back method with distant observation [10] was used to confirm this important performance factor of the sun dish. The colour look-back method was not used to align the dish, the alignment was previously done using the aim-point strategy technique, with the colour look-back method only being used to verify the intercept factor. The setup for intercept factor testing consisted of a colour target with an inner disc of 160 mm, bluish-purple in colour and an outer ring of approximately 400 mm, green in colour. This target was mounted close to the focal plane of the dish and images were taken along the axis of the dish at a distance of approximately 350 m with a digital camera. Subsequently, image-processing software was used to determine that approximately 99.3% of the reflected sunrays were focused into a 160 mm aperture. Test Results are shown in Fig. 3. The aperture of the OTSSG is set at 190 mm to allow for movement of +/- 15 mm of the centroid of the sunspot during the entire operational day. The allowable movement of the sunspot during operations is caused by a variety of effects including changing wind loading on the dish and gravitational forces at varying elevation.

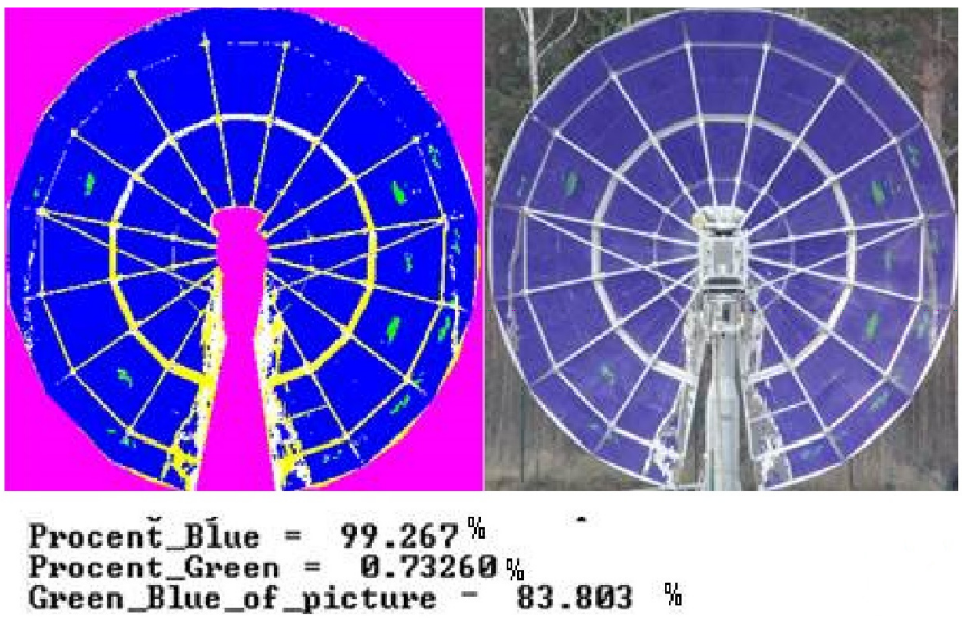


FIGURE 3. Intercept Factor test by colour look-back technique & distant observer method

Tracking Stability Testing

Tracking stability was tested for a sample of eleven dishes at different times of day to account for gravitational and wind loading effects at varying dish elevation angles. The tests were carried out at varying wind conditions ranging from completely still conditions to winds gusting at 16.6 m/s equating to the maximum operating wind speeds. The movement of the sunspot centroid was recorded at one-second intervals for periods of ten minutes with help of a CCD camera and ceramic glass plate; thirty such logs were collected for each solar dish. The objective of the test was to ensure that the intercept factor was maintained at the OTSSG aperture under real time tracking and operation conditions of the dish. The results are shown in following graphs in Fig. 4, elaborating the maximum sunspot displacement in the x and y axes. High sunspot displacement readings indicate that high wind conditions were prevalent at the time of testing. It was concluded from this test campaign that there was no negative effect on the intercept factor during the operation of the dish under varying wind and gravitational loads and the dish tracking control algorithms were capable of ensuring that the concentrated sunspot remained inside the receiver aperture opening at all times.

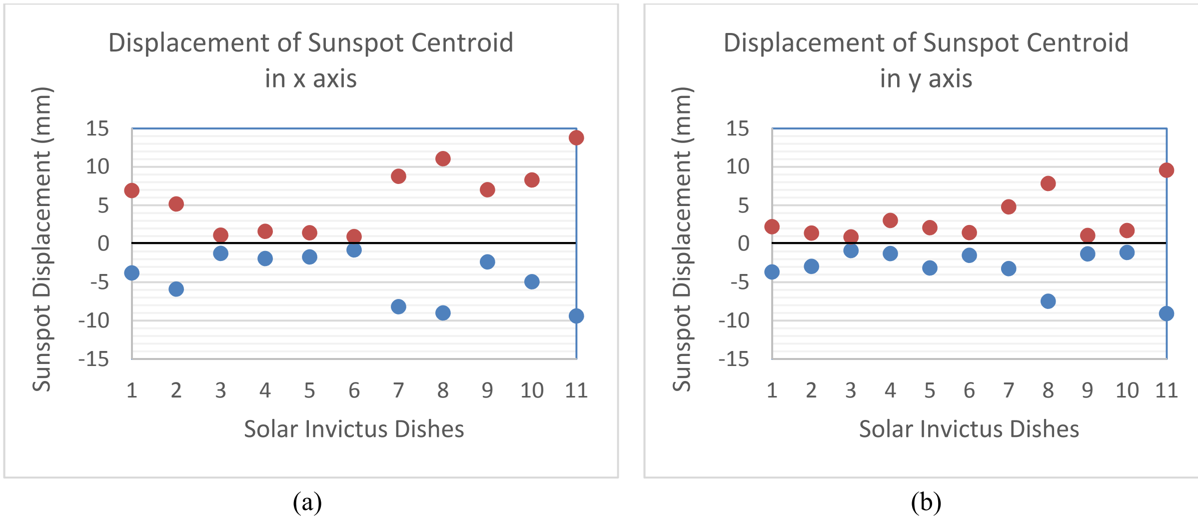


FIGURE 4. Maximum sunspot displacement in the x (a) and y axis (b) at focal plane during 'on sun' tracking

Thermal Efficiency Measurement Test

Test Setup and Instrumentation

Thermal efficiency tests were conducted on the Solar Invictus system installed at ZED Solar test facility to verify the actual performance of the system against the design objectives. The objective was to evaluate the thermal performance of the OTSSG by taking real measurements and establishing the net solar to steam efficiency curve for Solar Invictus over a range of temperature of up to 600°C.

Schematics of the test system as setup and boundaries are shown in Fig. 5. Input feed water was supplied to the system using a positive displacement type pump. System piping consists of a combination of fixed and flexible piping capable of withstanding temperatures of up to 600°C and pressures of up to 200 bar. Flexible piping was kept to the minimum possible but is required to allow dual axis tracking as well as thermal expansion. A backpressure valve was installed at the steam exit point to maintain desired system pressure.

Inline thermocouples were used to measure working fluid temperature at the inlet and outlet of the OTSSG, additionally a third thermocouple was placed at the steam exit point in order to be able to calculate piping related thermal losses. Insulating all the hot side piping with standard levels of insulation reduced such thermal losses. System pressures were recorded using pressure transducers at the inlet and outlet of the OTSSG. The volume flow rate of the feed water was measured using a turbine type flow meter installed on the inlet pipeline. The mass flow rate was computed by using the recorded volume flow rate and density of water at the measured inlet temperature and pressure.

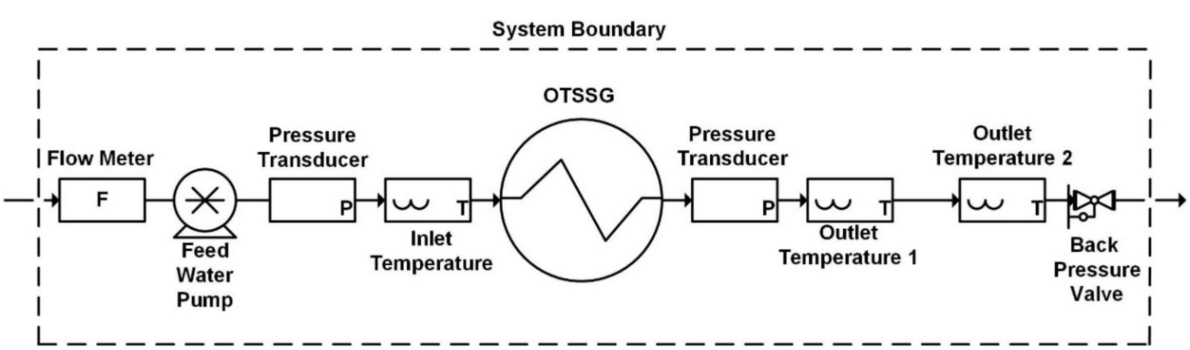


FIGURE 5. Schematic of thermal efficiency measurement test setup

A properly calibrated Kipp & Zonen pyrheliometer with temperature compensation (CHP1) was used for DNI measurements. Data from all sensors was fed into the proprietary Solar Steam Quality Control System (SSQCS) at standardised one-second intervals. The SSQCS logs and processes all incoming data, regulating the flow of the feed water to maintain the set steam output conditions according to varying DNI conditions throughout the day.

Test Procedure and Results

The Solar Invictus is able to produce pressurised hot water, saturated steam and superheated steam. To determine the thermal efficiency of the OTSSG, all tests carried out for the purposes of this paper were done so generating superheated steam (sensible heat region) at all times. There was no haze but detached dense cloud patches were rolling in and out during the day. Average ambient temperatures were 30°C with variable 6 m/s and relative humidity of 70%. Inlet water temperatures were stable between 27°C and 28°C. The mirrors were cleaned immediately before the start of the tests and the OTSSG unit was chemically descaled.

The SSQCS maintained superheated steam at an average temperature of 320°C. Thermal efficiency of the OTSSG was calculated at 92.4% ± 4.6% with 95% confidence interval based on the obtained experimental data. Uncertainty in the calculated thermal efficiency was estimated using Monte Carlo simulations [11]. Figure 6 presents a sample of the calculated efficiency and recorded DNI over a period of one hour during which the sky was largely clear with stable and relatively high DNI values. The graph is based on averages of 30 seconds intervals.

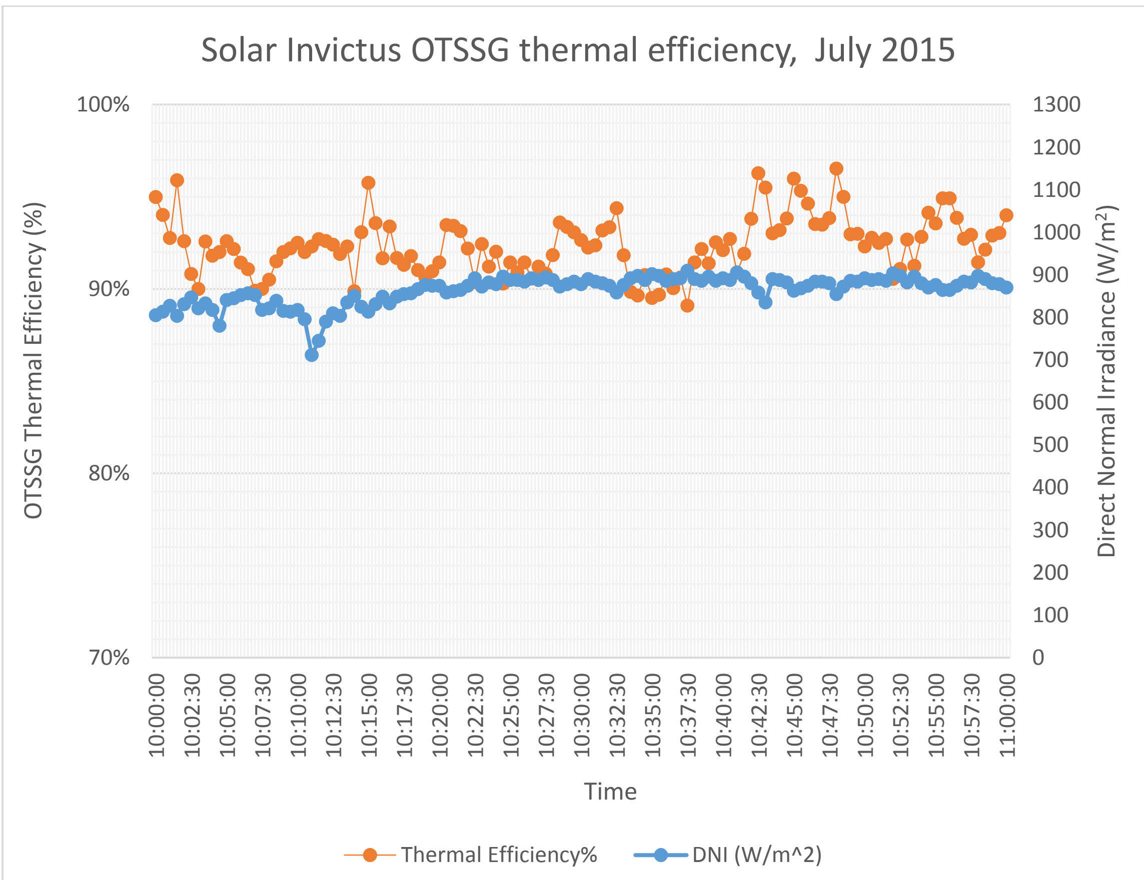


FIGURE 6. Thermal efficiency measurement test results for OTSSG

Data Reduction

To determine the net efficiency of the Solar Invictus both optical and thermal efficiencies were calculated. Optical efficiency, $\eta_{optical}$, provides the percentage amount of the incident solar energy on solar dish projected area that enters receiver aperture. It is a function of parameters that includes mirror reflectivity, γ, and intercept factor, IF, at receiver aperture which is measured experimentally.

$$\eta_{optical} = \gamma \cdot IF \tag{1}$$

Optical efficiency of the system provides the heat input, $Q_{optical}$, in the OTSSG, which is the product of projected area of the receiver, $A_{projected}$, and DNI.

$$Q_{optical} = DNI \cdot A_{projected} \cdot \eta_{optical} \tag{2}$$

Specific enthalpies at inlet, $h_{f\ in}$, and outlet, $h_{super\ heated}$, are obtained by corresponding pressures and temperatures. Energy transferred to the fluid (Q_{fluid}) in OTSSG is obtained by the product of enthalpy gain of the fluid, i.e. the difference between outlet and inlet enthalpies and mass flow rate, m', of the fluid [12]. While Solar Invictus was set to produce superheated steam; equation Eq. (3) is used.

$$Q_{fluid} = m'(h_{\text{super heated}} - h_{f\,in}) \tag{3}$$

Thermal efficiency ($\eta_{thermal}$) of the receiver is obtained by the ratio Q_{fluid} and $Q_{optical}$.

$$\eta_{thermal} = \frac{Q_{fluid}}{Q_{optical}}$$

With the measured optical and thermal efficiencies, net sun to steam efficiency, η_{net}, of the system was calculated which is the product of thermal and optical efficiency.

$$\eta_{net} = \eta_{optical} \cdot \eta_{thermal} \tag{4}$$

System was operated over a range of temperatures to obtain the thermal efficiency at different temperatures. Temperature dependent net efficiency curve for Solar Invictus was established as provided in Fig. 7.

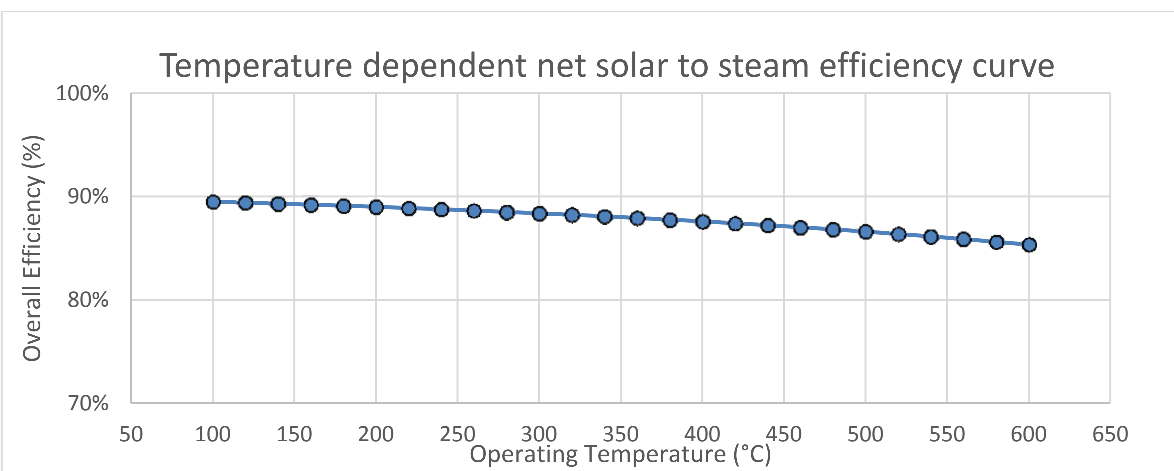


FIGURE 7. Net sun to steam efficiency of Solar Invictus established at DNI 850 W/m^2

CONCLUSION

The results presented in this paper provide conclusive evidence that the Solar Invictus system achieves industry-leading net solar-to-steam efficiency of over 88% under the applied steam conditions. The extremely low levels of losses from the OTSSG help to ensure an almost flat efficiency curve across the temperature ranges needed for real world applications. This makes the system ideally suited for high temperature and pressure, direct steam injection applications such as solar thermal enhanced oil recovery for extracting heavy oil.

Based on the analysis in this paper, the patented ZED Solar parabolic dish achieves a substantially higher level of optical efficiency than the highest known performance of existing parabolic trough and tower systems. The mirrors reflect back 96.1% of the solar irradiation incident on the dish and achieving a 99.3% intercept factor of the reflected solar rays into the receiver aperture results in a net 95.4% optical efficiency.

The wide temperature and pressure ranges make the system extremely flexible and well suited to many applications. It is even possible to run steam turbines without requiring a gas fired booster unit to achieve the required temperatures.

Furthermore, the tests outlined in this paper confirm that a single unit can on its own achieve application dependent steam conditions that traditional solar solutions can only achieve at park level.

In conclusion, it can be confidently said that this system has the potential to be a game changer for the CSP industry.

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